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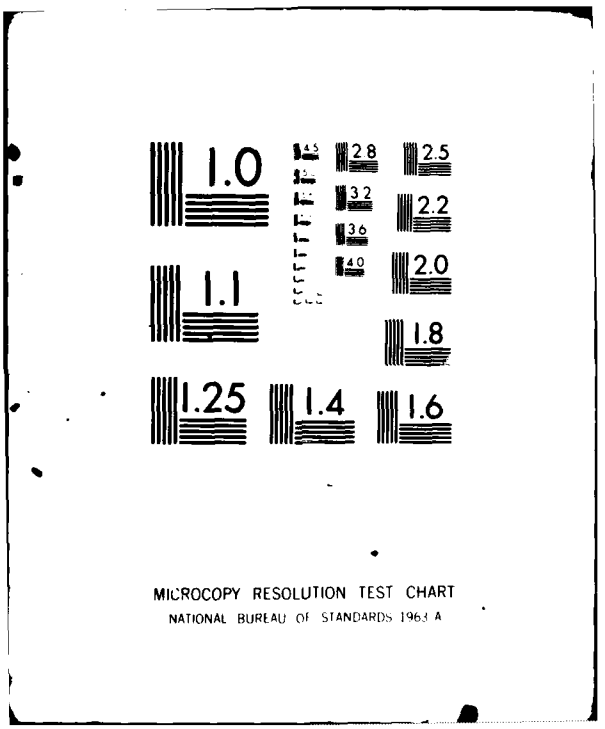
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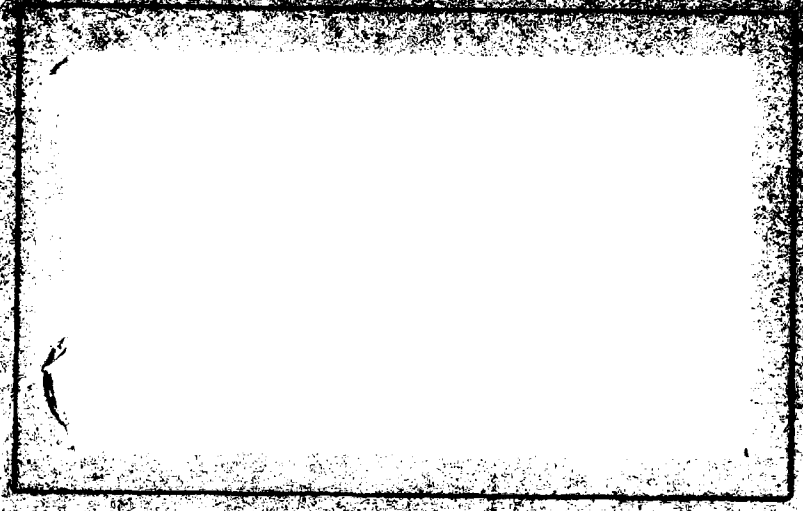

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Applied Research in Statistics - Mathematics - Operations Research

FINAL REPORT

STATISTICAL RESEARCH ON PROBLEMS ASSOCIATED WITH NAVY FIRE PROTECTION AND FUEL TECHNOLOGY PROGRAMS

by

Dennis E. Smith

TECHNICAL REPORT NO. 109-1

October 1981

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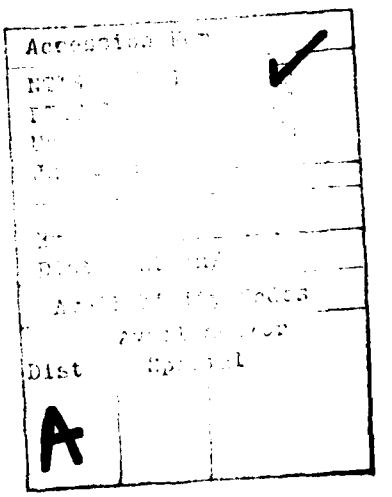

I. INTRODUCTION

This final technical report on Contract No. N00014-77-C-0661 summarizes a research investigation conducted by Desmatics, Inc. under sponsorship of the Office of Naval Research. The Desmatics study has been devoted to statistical research in a number of problem areas associated with fire protection and fuel technology programs being conducted by the Combustion and Fuels Branch of the Naval Research Laboratory (NRL).

The following section of this report briefly reviews the statistical research effort in the main problem areas addressed by Desmatics. The final section provides a reference list of informal technical notes, prepared under this contract, which were submitted to the cognizant NRL scientists.

II. RESEARCH REVIEW

The Desmatics techical effort under Contract No. N00014-77-C-0661 provided statistical research support for ongoing programs in the Combustion and Fuels Branch of NRL. In general, this statistical support was evolutionary in nature, involving discussion of the particular problem under consideration, design of appropriate experiments, analysis of experimental data, documentation of findings, and recommendations for possible future experiments.

Attention was primarily concentrated on four program areas. These are the qualification of fire extinguishing agents, the examination of the effects of fuel composition on its freezing point, the evaluation of the accuracy of refractometers and spectrometers in analyzing aqueous film forming foam (AFFF) concentrations, and the study of fire suppression through nitrogen pressurization. The statistical research in each area was documented by informal technical notes (listed in Section III), which were distributed by Desmatics to cognizant NRL personnel. The following sections briefly review the statistical research within these four areas.

A. QUALIFICATION OF FIRE EXTINGUISHING AGENTS

Statistical research on the qualification of fire extinguishing agents was focused on two main problems. One was the possibility of scaling the results of small fires to large fires. The other was the examination of alternatives to the 40-second summation. This research, which is summarized in the following paragraphs, was described in Technical Notes No. 109-2,

No. 109-6, No. 109-11, No. 109-13, No. 109-16, and No. 109-17.

Qualification tests of fire extinguishing agents are conducted in accordance with military specification MIL-F-24385A. The data from these tests consists of observed 40-second summation scores for three sizes of fires: 28 square foot, 50 square foot and 1260 square foot. For economic and environmental reasons, it is desired to eliminate the 1260 square foot fires in future tests. Therefore, the possibility of scaling results of the smaller fires to the 1260 square foot fires was examined.

Although the lack of balance in the existing data base prevented definite conclusions about the possibility of scaling, an analysis was performed on the available data to determine whether the information obtained would be useful in attempting to arrive at a conclusion. Based on this analysis, a predictive equation was developed for agents mixed at full strength concentration. Despite the fact that the predictive equation provided a fairly good fit to the observed data, its usefulness is somewhat questionable because of the small number of data points from which it was developed.

Although the results are encouraging with respect to the possibility of scaling separately for each concentration level, there remains a lack of balanced data which makes conclusions difficult to reach. It has been recommended that additional experimental runs be made to create a more balanced data set and therefore provide a better indication of the possibility of developing a general scaling procedure.

Related research examined the 40-second summation score, one criterion currently used to evaluate fire extinguishing agents. Ideally, this score should be the best measure of an agent's extinguishing ability that could be extracted from the 10, 20, 30 and 40 second scores. If the information available in the four scores could be combined in another way to yield a

more accurate measurement, the chances of accepting an ineffective agent or rejecting an effective agent would be reduced. Thus, two alternative measurement methods were investigated.

A comparison of the three methods of measuring extinguishing ability suggested that, although the three methods result in different scores, comparisons of agents based on any of the three methods would lead to similar conclusions. Therefore, it appears that there is not sufficient evidence to justify a change from the current use of the 40-second summation method.

B. THE EFFECT OF FUEL COMPOSITION ON ITS FREEZING POINT

Because of the usefulness of a jet fuel with a low freezing point, it is desirable to investigate how fuel composition affects its freezing (melting) points. In the particular problem under consideration, interest was focused on mixtures of the seven normal alkanes C_{10} through C_{16} and a base stock of fixed composition. Mole fraction, which provides a more meaningful measure than weight fraction, was used to characterize the various mixtures studied.

In an attempt to obtain the most information from a set of experimental observations, a series of statistically-designed experiments was conducted. The sequential nature of these experiments meant that decisions about how each experiment should be set up could be based on information from the preceding experiments. It should be noted that these experiments had to take into consideration the fact that a mixture system was being examined.

In experiments with mixture systems, the observed response (octane rating of a gasoline or tensile strength of an alloy, of example) is usually

a function only of the proportions of components and not of the total amount of the mixture. Because of constraints on the components, standard statistical experimental designs are of limited use; specialized mixture designs have been developed especially for this reason.

One commonly used type of mixture design provides information uniformly over the entire range of possible mixtures. This general type of design, modified for the existence of upper or lower bounds on some of the components, was used by Desmatics in specifying the first two fuel mixture experiments.

The overall series of experiments has revealed that C_{12} and C_{13} have strong negative effects on the melting point, while C_{14}, C_{15} and C_{16} have strong positive effects. Furthermore, there is a strong interaction between the alkanes C_{12}, C_{13} and C_{16}. Although, in general, C_{12} and C_{13} interact with each other, the nature of this interaction changes as the mole fraction of C_{16} changes. A relatively detailed discussion of the experiments and their results is given in Desmatics Technical Notes No. 109-4, No. 109-12, No. 109-15, No. 109-18, No. 109-19, No. 109-21, No. 109-23, No. 109-24, No. 109-26, No. 109-29, No. 109-30, No. 109-36, No. 109-37, and No. 109-40.

C. EVALUATION OF THE ACCURACY OF REFRACTOMETERS

Aqueous film forming foam (AFFF) has proved to be an extremely good fire extinguishing agent. To be effective, however, an AFFF solution must contain the proper concentration of AFFF. Thus, it is necessary to conduct routine maintenance tests of concentrations produced by proportioning systems aboard ships. Such tests may be based on the use of a refractometer or a spectrometer.

A preliminary experiment to study the accuracy with which different refractometers can measure AFFF concentration involved seven refractometers, seven AFFF agents and three operators. For each AFFF agent, ten solutions with different concentrations were used throughout the experiment. The true concentration of each solution was known by the experimenter but the operators were not told these true concentrations.

Examination of the resulting observed data indicated that the errors were not a percentage of the true concentration, but rather relatively constant over the range of concentrations. For this reason the absolute error in recorded concentration was used in the analysis.

An analysis of variance revealed that the accuracy of the recorded concentrations was significantly different for different refractometers, agents and operators. However, in some cases one operator was more accurate with a given refractometer than was another operator, but was less accurate with other refractometers. Because of such interactions, it is not possible to state that a particular refractometer will unconditionally provide the most accurate concentration readings.

To provide more definitive conclusions, a follow-up experiment was designed. The analysis of the experimental data again revealed significant interactions, which required an examination of statistical contrasts. Technical Note No. 109-44 discusses this follow-up experiment in detail. Related material is given in Technical Notes No. 109-8, No. 109-32, No. 109- 35, and No. 109-43.

D. FIRE SUPPRESSION THROUGH NITROGEN PRESSURIZATION

Another fire protection measure being investigated by NRL is nitrogen

pressurization, which is based on the fact that while it is the percentage of oxygen which is necessary to sustain fire, it is the partial pressure of oxygen which is necessary to sustain life. Thus, by pressurizing with nitrogen, a fire can be extinguished without harm to life.

To design an effective nitrogen pressurization system requires that fire characteristics be quantified. However, fires are very complex phenomena which are not fully understood. Thus, Desmatics designed statistical experiments to gather data which could aid in modeling and/or characterizing fires.

These statistically-designed experiments, an extension of previous Class A fires, had the primary objective of determining the optimal atmospheric pressure, that is, the minimum atmospheric pressure which will efficiently extinguish the fire. At the onset of the research investigation, six factors (nitrogen delivery rate, circulation, preburn time, fuel size, fuel orientation, and observer) were specified for examination. The major dependent variable of interest was flaming time, the elapsed time from the end of preburn to the extinguishment of the flames. Attention was, of course, also paid to chamber pressure at flame out, since the question to be answered is how much nitrogen is required to suppress a fire having certain characteristics.

As in most studies, the experiments were sequential in nature. These experiments and the analysis of their results are discussed in Desmatics Technical Notes No. 109-3, No. 109-5, No. 109-7, No. 109-9, No. 109-10, No. 109-14, No. 109-20, No. 109-22, No. 109-25, No. 109-27, No. 109-28, No. 109-31, No. 109-33, No. 109-34, No. 109-39, and No. 109-42.

III. TECHNICAL NOTES

In the preceding section, reference was made to a number of informal technical notes which describe various aspects of the statistical research conducted by Desmatics, Inc. under Contract No. N00014-77-C-0661. The following is a complete listing of the technical notes prepared under this contract:

Note No.	Date	Title
109-1	17 Nov 77	SUGGESTED INITIAL EXPERIMENT FOR STUDYING THE CORROSION EFFECTS OF HALON USED AS A FIRE SUPPRESSANT
109-2	23 Nov 77	A DISCUSSION OF SOME STATISTICAL ASPECTS OF QUALIFYING FIRE EXTINGUISHING AGENTS
109-3	7 Dec 77	AN INITIAL EXPERIMENT TO STUDY THE NITROGEN PRESSURIZATION REQUIRED TO EXTINGUISH A FIRE
109-4	15 Mar 78	A STATISTICAL EXPERIMENT FOR INVESTIGATING THE EFFECTS OF FUEL COMPOSITION ON ITS FREEZING POINT
109-5	20 Mar 78	RESULTS OF THE STATISTICAL ANALYSIS OF THREE RESPONSE VARIABLES FOR A NITROGEN PRESSURIZATION EXPERIMENT
109-6	13 Apr 78	A PRELIMINARY EXAMINATION OF THE POSSIBILITY OF SCALING IN QUALIFICATION TESTS OF FIRE EXTINGUISHING AGENTS
109-7	14 Apr 78	RESULTS OF THE STATISTICAL ANALYSIS OF FLAMING TIME AND SMOLDERING TIME FOR A NITROGEN PRESSURIZATION EXPERIMENT
109-8	26 Apr 78	A SUGGESTED EXPERIMENT FOR EVALUATING THE ACCURACY OF REFRACTOMETERS AND SPECTROMETERS IN ANALYZING AFFF CONCENTRATIONS

109-9	15 May 78	A FOLLOW-UP NITROGEN PRESSURIZATION EXPERIMENT USING CARDBOARD AS FUEL
109-10	28 Jun 78	AN EXPERIMENT TO STUDY NITROGEN PRESSURIZATION ON FIRES FOR FOUR FUEL TYPES
109-11	17 Aug 78	A SUGGESTED EXPERIMENT FOR EXAMINING THE SCALING OF QUALIFICATION TESTS
109-12	8 Sep 78	A REVISED EXPERIMENT FOR INVESTIGATING THE EFFECTS OF FUEL COMPOSITION ON ITS FREEZING POINT
109-13	25 Oct 78	A DISCUSSION OF THE 40-SECOND SUMMATION AND TWO ALTERNATIVE STATISTICS
109-14	11 Jan 79	RESULTS OF THE STATISTICAL ANALYSIS FOR THE NITROGEN PRESSURIZATION FOLLOW-UP EXPERIMENT
109-15	9 Mar 79	NOTES ON A PREDICTIVE EQUATION FOR FREEZING POINT
109-16	26 Mar 79	A COMPARISON OF THE 40-SECOND SUMMATION AND TWO ALTERNATIVES
109-17	28 Mar 79	FURTHER CONSIDERATION OF THE POSSIBILITY OF SCALING IN QUALIFICATION TESTS OF FIRE EXTINGUISHING AGENTS
109-18	28 Mar 79	ADDITIONAL COMMENTS ON A PREDICTIVE EQUATION FOR FUEL FREEZING POINT
109-19	18 Apr 79	A FOLLOW-UP EXPERIMENT FOR INVESTIGATING THE EFFECTS OF FUEL COMPOSITION ON ITS FREEZING POINT
109-20	16 May 79	EVALUATION OF THE PRESSURE OVERSHOOT PROBLEM FOR THE INITIAL NITROGEN PRESSURIZATION EXPERIMENT
109-21	17 May 79	A REVISED FOLLOW-UP EXPERIMENT FOR INVESTIGATING THE EFFECTS OF FUEL COMPOSITION ON ITS FREEZING POINT

109-22	1 Jun 79	SOME ADDITIONAL COMMENTS ON THE RESULTS OF THE NITROGEN PRESSURIZATION FOLLOW-UP EXPERIMENT FOR CARDBOARD FIRES
109-23	19 Jun 79	A SECOND REVISION OF A FOLLOW-UP EXPERIMENT FOR INVESTIGATING THE EFFECTS OF FUEL COMPOSITION ON ITS FREEZING POINT
109-24	26 Jul 79	A DISCUSSION OF EXPERIMENTAL DESIGNS FOR MIXTURE PROBLEMS
109-25	20 Aug 79	SUMMARY OF CONCLUSIONS FROM THE FLAMING TIME ANALYSIS OF THE FOUR FUEL AND FOLLOW-UP CARDBOARD FUEL EXPERIMENTS
109-26	10 Sep 79	ANALYSIS OF A FOLLOW-UP FUEL FREEZING POINT EXPERIMENT
109-27	19 Sep 79	RESULTS OF THE STATISTICAL ANALYSIS FOR THE FOUR FUEL EXPERIMENT
109-28	26 Sep 79	RESULTS OF REVISED STATISTICAL ANALYSIS FOR THE FOLLOW-UP CARDBOARD FUEL EXPERIMENT
109-29	31 Oct 79	COMPARISON OF PREDICTION EQUATIONS FROM TWO MIXTURE EXPERIMENTS
109-30	19 Nov 79	CLARIFICATION OF NOTATION USED IN FUEL FREEZING POINT EXPERIMENTS
109-31	28 Nov 79	RESULTS OF THE ANALYSIS FOR SMOLDERING TIME IN THE FOUR FUEL EXPERIMENT
109-32	28 Dec 79	AN EXPERIMENT FOR EVALUATING THE ACCURACY OF REFRACTOMETERS AND SPECTROMETERS IN ANALYZING AFFF CONCENTRATIONS
109-33	31 Dec 79	AN EXPERIMENT TO STUDY FREE-BURNING FIRES IN A LARGE CHAMBER

109-34	7 Jan 80	ANALYSIS OF THE BURNING RATE DURING THE PREBURN PERIOD FOR THE FOLLOW-UP CARDBOARD FUEL EXPERIMENT
109-35	9 Jan 80	RESULTS OF THE STATISTICAL ANALYSIS OF THE ACCURACY OF REFRACTOMETERS IN ANALYZING AFFF CONCENTRATIONS
109-36	27 May 80	A SECOND FOLLOW-UP EXPERIMENT FOR INVESTIGATING THE EFFECTS OF FUEL COMPOSITION ON ITS FREEZING POINT
109-37	6 Jun 80	ADDENDUM TO TECHNICAL NOTE NO. 109-36
109-38	18 Jul 80	ADDITIONAL STATISTICAL ANALYSIS OF A TIME-INTEGRATED SAMPLING EXPERIMENT
109-39	8 Sep 80	A REVISED EXPERIMENT TO STUDY FREE-BURNING FIRES
109-40	12 Dec 80	A STATISTICAL EXAMINATION OF THE EFFECT OF JET FUEL COMPOSITION ON ITS FREEZING (MELTING) POINT
109-41	12 Feb 81	APPENDIX FOR NRL REPORTS: THE ANALYSIS OF VARIANCE
109-42	13 Mar 81	A DISCUSSION OF AN EXPERIMENTAL PLAN FOR LARGE SCALE HULL INSULATION FIRE TESTS
109-43	30 Jul 81	TEST PLAN FOR AN EXPERIMENT TO STUDY REFRACTOMETERS AND AFFF AGENTS
109-44	8 Sep 81	A STATISTICAL ANALYSIS OF REFRACTOMETER ACCURACY

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